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Understanding production potentials and yield gaps in intensive maize production in China

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ABSTRACT

Understanding yield potentials and exploitable gaps in current intensive maize (*Zea mays* L.) production is essential in order to increase grain yields to meet future food requirements amid strong competition for limited resources. In this study, we used simulations with the Hybrid-Maize Model (http://www.hybridmaize.unl.edu/), highest recorded yields published in the literature, field experiments, and farm survey data to assess yield potentials and gaps in four maize agro-ecological regions of China. In 50 simulations of high-yield sites across China from 1990 to 2009, the yield potential averaged 16.5 Mg ha^{-1} for irrigated maize and 13.9 Mg ha^{-1} for rainfed maize, respectively. During the same period, the highest recorded yield was 15.4 Mg ha^{-1}, or 93% of the yield potential of irrigated maize. In comparison, the average farmer's yield was 7.9 Mg ha^{-1} based on 5584 farms surveyed in 2007–2008. Consequently, the yield gap between the average farmer's yield and the modeled yield potential (YG_M) was 8.6 Mg ha^{-1} for irrigated maize and 6.0 Mg ha^{-1} for rainfed maize and so farmers attained 48–56% of the yield potential. The yield gap between the average farmer's yield and highest recorded yield (YG_R) was 7.6 Mg ha^{-1}, so farmers attained 51% of the recorded yield. Because the sites used for simulated and recorded yields possessed the most favorable combinations of soil and crop management, closing the gaps in YG_M and YG_R in farmers' fields within a short time frame could be very difficult. The attainable yield was collected from field experiments, which were conducted in farmers' fields by farmers using recommended management practices by local agronomists. The data for attainable yield averaged 12.3 Mg ha^{-1} according 137 field experiments across China. The yield gap between the average farmer's yield and the experimental yield (YG_E) was 4.5 Mg ha^{-1}, with farmers attaining 64% of the experimental yield. The main factor explaining this gap was inefficient crop management practices, which constrained yield improvements in farmers' fields. In order to narrow this gap, multidisciplinary understanding and cooperation among the disciplines of plant science, agronomy, soil science, agro-ecology and extension, resulting in integrated soil–crop system management, are essential.

1. Introduction

To meet the needs of the Chinese population, expected to peak at 1.5 billion in 2033, grain production must increase by at least 35% during the next 20 years (Zhang, 2011). Achieving this without expanding cultivation into natural ecosystems will depend on raising yield potentials and grain yields by closing existing yield gaps to avoid yield stagnation in some of the nation's most productive systems (Cassman et al., 2003). Because of the great difficulty of increasing yield potential over the short term through genetic improvement (Tollenaar and Lee, 2002), closing the existing yield gaps between attainable potential and farmers' yields is essential to ensure national food security. Understanding the factors underlying yield gaps is necessary to increase future food production capacity and to help formulate policies.

Yield potential is defined as the yield of a crop cultivar when grown in environments to which it is adapted, with unlimited nutrients and water and with pests and diseases effectively controlled (Evans, 1993). It can be measured in various ways, including using model simulations, field experiments, yield contests, and data on maximum farmer yields (Lobell et al., 2009). Crop models can provide reasonable estimates of yield potential when historical weather data are available (Grassini et al., 2011). Some studies have also attempted to quantify yield potential using observed field data (Sadras et al., 2002; Tittonell et al., 2008). However, lack of data from well-designed experiments that effectively control limiting factors has restricted the reliability of quantifications of yield potential based on actual measurements (Duvick and Cassman, 1999).

The difference between yield potential and the actual yield achieved by farmers represents the exploitable yield gap (Cassman

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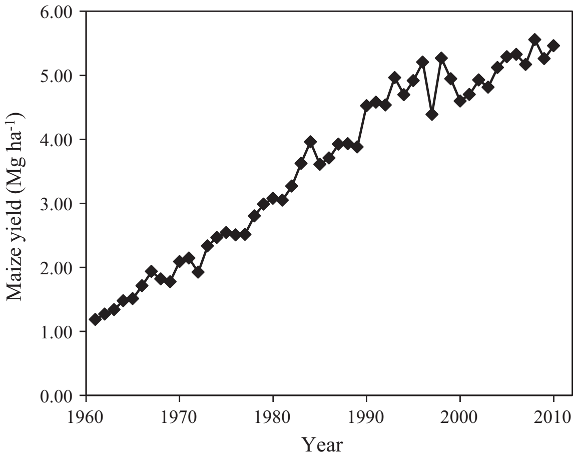

Fig. 1. Changes in maize grain yield in China from 1961 to 2010 (FAO, 2012).

et al., 2003). The assessment of yield potential and yield gaps can help identify limiting factors and develop strategies to improve crop productivity (Aggarwal and Kalra, 1994; Naab et al., 2004; Bhatia et al., 2008). In recent years, crop yield gaps have been evaluated extensively worldwide (Ahrens et al., 2010; Licker et al., 2010; Neumann et al., 2010). However, these studies have received limited attention in China. Studies in China have measured yield potential mainly through an examination of highest recorded yields and model simulations (Liang et al., 2011; Wang et al., 2012). Hence, yield potential has usually represented the highest possible yield achieved under the most favorable combinations of soil, climate, and crop management in selected locations. Thus, these yield potentials are difficult to achieve because of the lack of experimental field data obtained under conditions similar to those in farmers' fields. To some extent, this reduces farmers' initiative. In addition, regional evaluations of yield gaps have received little attention because of the lack of large-scale farm survey data, which are difficult to obtain due to the millions of farm households in China.

Maize, the second-largest food crop in China, accounts for more than one-third of Chinese cereal production and is responsible for 19% of global maize output (FAO, 2012). Until the mid 1990s, Chinese maize grain yield increased in a near-linear fashion, but has stagnated at around 5 Mg ha^{-1} since 1995 (Fig. 1). Average annual growth rates declined from 5–8% in 1960–1980s to <1% in the past 20 years. However, some studies have shown that the potential maize yield is more than 15 Mg ha^{-1} in many regions of China. For example, mean maize yields were found to be >15 Mg ha^{-1} from 2006 to 2010 at 159 sites in China (Chen et al., 2012b), with the highest maize grain yield being 19 Mg ha^{-1} in Shandong Province (Li and Wang, 2009). These observations suggest the possibility of large yield gaps in maize production. Thus, quantifying these gaps is essential to identify the possible degree of yield improvement attainable in the near future to ensure food security in China.

In the present study, we quantified yield potentials and variation therein using the Hybrid-Maize Model and maximum yields published in the literature, evaluated yield averages and variation of farmers' fields through farm survey data and field experiments with optimal management, and assessed maize yield gaps and yield gap variation of major maize agro-ecological regions of China.

2. Materials and methods

2.1. Description of China's maize regions

Fig. 2 shows the area in China sown to maize, based on 2003 county-level data (National Bureau of Statistics of China, 2003). Generally, the maize agro-ecological regions in China can be divided into four to six zones (Qiu et al., 2003), but we broadly classified them into four regions from north to south: Northeast China (NE China), North China Plain (N China Plain), Northwest China (NW China), and Southwest China (SW China, Fig. 2). From 2005 to 2009, the maize area of these four regions averaged 10.3, 10.0, 2.4, and 3.8 million ha, respectively (China Agriculture Database, 2012). The corresponding maize production was 58.1, 55.4, 12.8, and 17.0 million tons, respectively.

The NE China region is located mainly north of 40.0°N. The climate is frigid humid or semi-humid temperate and is characterized by warm, wet summers and long, cold winters. According to 1970–2009 climate records from 72 meteorological stations across this region, the mean temperature averaged 4.9 °C and ranged from −0.5 °C to 11.1 °C (Chen et al., 2012a). Mean precipitation was 594 mm, 60% of which fell from July to September. Because early frosts usually appear in September and early October, maize is generally sown in spring (April or May). In NE China, rainfed maize is prevalent although maize has come under irrigation in many areas of this region recently.

The N China Plain, at latitudes of 31.4–42.7°N, has a warm, semi-humid continental monsoon climate. Winter is cold and dry, whereas summer is hot and wet. The annual average temperature ranges from 8 °C to 15 °C (Guo et al., 2010). Annual precipitation is extremely variable, ranging from 300 mm to 1000 mm, with an average of about 500 mm (Li et al., 2005), of which 70–80% falls in summer. A winter wheat/summer maize rotation, with two harvests per year, is the main cropping system. Summer maize is seeded in early June, immediately after the winter-wheat harvest, and harvested at the beginning of October. A little irrigation is used during the maize growing season at critical stages, such as emergence and silking, to avoid water stress and ensure a high yield (Meng et al., 2012).

In NW China, the annual temperature averages 7.5 °C, ranging from 1 °C to 14.9 °C. In most areas of this region, precipitation is less than 200 mm. Continuous spring maize cropping is the major maize system. Due to seasonal droughts, fields are irrigated in many areas to achieve high grain yields.

In SW China, the annual temperature averages 15–18 °C and precipitation is about 1200 mm. Maize is grown in both summer and spring. As in NW China, seasonal droughts have led to an increase in irrigation adoption to increase yields.

2.2. Database description

2.2.1. Modeled yield potential

The Hybrid-Maize Model is a process-oriented model that can simulate maize yield potential under growth conditions that are not limited by nutrient deficiencies, toxicities, insect pests, disease, or weeds. The model has been shown to be reasonably accurate at estimating maize yield potential (Yang et al., 2004, 2006). Recently, it has been tested and widely used in the U.S. (Grassini et al., 2009, 2011; Setiyono et al., 2011), South Asia (Timsina et al., 2010), and China (Bai et al., 2010; Chen et al., 2011). This model can simulate climate-driven yield potential under both optimum water and rain-fed conditions. Model input includes weather data (*i.e.*, solar radiation, maximum and minimum temperatures), sowing and harvest dates, and density. In the present study, 50 sites which had published data from high-yielding fields in the four maize regions from 1990 to 2009 (Yin, 2000; Wang et al., 2004; Chen et al., 2008; Li and Wang, 2010), were chosen to simulate the yield potential for the whole of China. Of these 50 sites, 14 were located in NE China, 21 on the N China Plain, 12 in NW China, and 3 in SW China (Table 1). Solar radiation and maximum and minimum temperatures were obtained from nearby meteorological stations (CMA archives, 2012), which were always away from the sites around

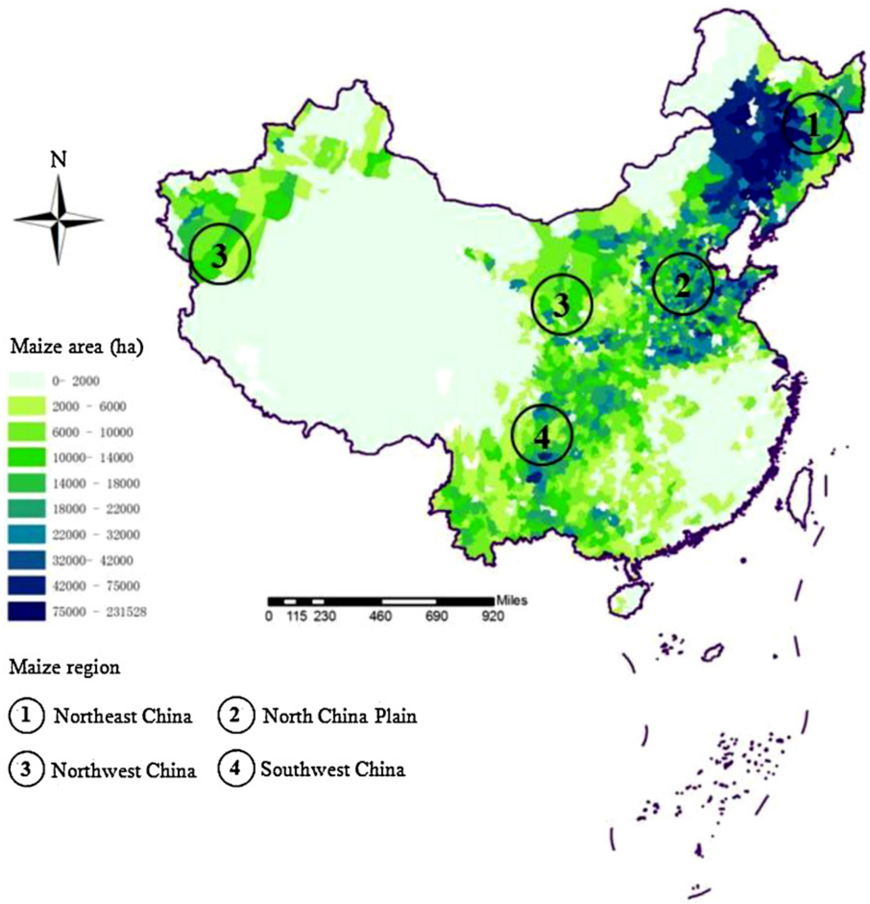

Fig. 2. Maize-growing area based on 2003 county-level data (National Bureau of Statistics of China, 2003) and four maize agro-ecological regions in China: Northeast China (NE China), North China Plain (N China Plain), Northwest China (NW China), and Southwest China (SW China).

20 km. Annual weather data during maize seasons for simulation at each site matched associated long-term observations (1990–2009) reasonably well. Sowing and harvest dates and site density were taken from studies published on each field (Yin, 2000; Wang et al., 2004; Chen et al., 2008; Li and Wang, 2010). In addition, sowing dates and hybrid maturities for simulations at each site were similar as local farmers'.

2.2.2. The highest recorded yield potential

The highest recorded yields were taken from published highest yield achieved by agronomists at the selected locations under the most favorable ecological conditions with extensive inputs, regardless of the economic costs and environmental risks (Chen et al., 2012b). To further assess yield potential, the highest recorded yields at the same 50 sites were also extracted from the literature for the same year as that simulated yield (Yin, 2000; Wang et al., 2004; Chen et al., 2008; Li and Wang, 2010). Thus, 50 data points were collected. Among 50 data points, sowing dates and hybrid maturities at each site were similar with local farmers'.

2.2.3. Experimental yield potential

Because the sites used to estimate yield potential and those with the highest recorded yields published in the literature were those with good ecological conditions and extensive inputs, farmers may

Table 1
Modeled yield potential for irrigated and rainfed maize using the Hybrid-Maize Model and the highest recorded yield in China and in the four maize agro-ecological regions: Northeast China (NE China), North China Plain (N China Plain), Northwest China (NW China), and Southwest China (SW China).

		Region				China[a]
		NE China	N China Plain	NW China	SW China	
Yield potential[b]	Ave. (Mg ha^{-1})	15.9[c] (15.4)[d]	17.6 (13.4)	19.5 (14.9)	12.8 (10.3)	16.5 (13.9)
	Range (Mg ha^{-1})	15.6–17.7 (11.9–17.5)	14.4–21.0 (9.6–21.0)	16.5–21.5 (11.3–19.6)	12.4–13.0 (9.2–11.3)	12.4–21.5 (9.2–21.0)
	SD[e] (Mg ha^{-1})	0.5 (1.6)	2.1 (4.1)	1.5 (3.9)	0.4 (1.0)	2.3 (3.6)
	Number (n)	14	21	12	3	50
Highest recorded yield[f]	Ave. (Mg ha^{-1})	15.8	16.3	17.3	11.0	15.4
	Range (Mg ha^{-1})	13.5–17.8	13.6–21.0	14.6–20.4	10.9–11.3	10.9–21.0
	SD (Mg ha^{-1})	1.2	2.2	1.8	0.3	2.3
	Number (n)	14	21	12	3	50

[a] Yield potential and highest recorded yield of China as a whole were the weighted averages of the maize-growing areas in the four maize regions from 2005 to 2009.
[b] Yield potential was simulated by the Hybrid-Maize Model.
[c] Value of irrigated maize.
[d] Value of rainfed maize.
[e] SD: standard deviation.
[f] Highest recorded yields were extracted from published reports (Yin, 2000; Wang et al., 2004; Chen et al., 2008; Li and Wang, 2010).

have great difficulty in attaining comparable yields. The attainable yield was collected from field experiments, which were conducted in farmers' fields by farmers using recommended management practices by local agronomists with lower economic costs and environmental risk compared with that in the highest recorded yield. Thus, experimental yield data were obtained under conditions similar to those in most farmers' fields, and attainable yield goals were estimated for 2005–2009. In all, data from 137 field experiments were collected: 11 in NE China, 18 on the N China Plain, 37 in NW China, and 71 in SW China. These experiments were based on the recommendations of local agronomists in the four maize regions as to crop varieties, sowing dates, density, management practices, and irrigation.

2.2.4. Average famers' yields

To evaluate on-farm yield and the yield gap between yield potential and actual yield achieved by farmers, farm surveys were conducted during 2007–2008. These covered 5584 farm households across China, with 1248 in NE China, 2623 on the N China Plain, 520 in NW China, and 1193 in SW China. The farm surveys included face-to-face interviews with farmers and the questions were designed to capture relevant data (*e.g.*, grain yield, density, harvest date, fertilizer and irrigation management). For China as a whole, average yield potentials, highest recorded yields, experimental yields, average farmers' yields, and yield gaps were based on weighted averages from the maize areas during 2005–2009 in the four maize regions.

2.3. Yield gap calculation

To aid comparisons of different yield levels, three yield gaps were defined based on different measures of yield potential or attainable yields: model-based yield gap (YG_M), highest recorded-based yield gap (YG_R), and experiment-based yield gap (YG_E). The three gaps were calculated using Eqs. (1)–(3).

$$YG_M = \text{Modeled yield potential} - \text{Average farmers' yield} \quad (1)$$

$$YG_R = \text{Highest recorded yield} - \text{Average farmers' yield} \quad (2)$$

$$YG_E = \text{Experimental yield} - \text{Average farmers' yield} \quad (3)$$

3. Results

3.1. Yield potentials and highest recorded yields

The modeled yield potential of the Hybrid-Maize Model and the highest recorded yields of China and for the four maize agro-ecological regions are shown in Table 1. On average, the modeled yield potential for irrigated maize across all 50 sites was 16.5 Mg ha^{-1} (range: 12.4–21.5 Mg ha^{-1}), with 13% variation for China. In all 50 sites, highest recorded yields achieved by agronomists in the year with favorable ecological conditions and extensive inputs, averaged 15.4 Mg ha^{-1} and ranged from 10.9 to 21.0 Mg ha^{-1}, with 14% variation. On average, the highest recorded yield was 93% of the yield potential of irrigated maize, thus nearly achieving yield potential.

As shown in Table 1, among the four regions, the highest average yield potential (19.5 Mg ha^{-1}) of irrigated maize was in NW China, followed by the N China Plain (17.6 Mg ha^{-1}), NE China (15.9 Mg ha^{-1}), and SW China (12.8 Mg ha^{-1}). The same regional order was found in average highest recorded yield, with 17.3 Mg ha^{-1} in NW China, 16.3 Mg ha^{-1} in the N China Plain, and 15.8 Mg ha^{-1} in NE China, which were 89% (range: 79–98%), 93% (75–99%), and 99% (95–100%) of the respective yield potentials. The lowest average highest recorded yield was 11.0 Mg ha^{-1} in SW China, which was 86% (84–88%) of the yield potential of irrigated maize. The regions varied widely in whether highest recorded yields achieved yield potentials showed the different level of management in different sites. Thus, this emphasized the importance of agronomic management and the need for caution in assuming the yield potential to be equal to the highest recorded yields in Chinese maize production.

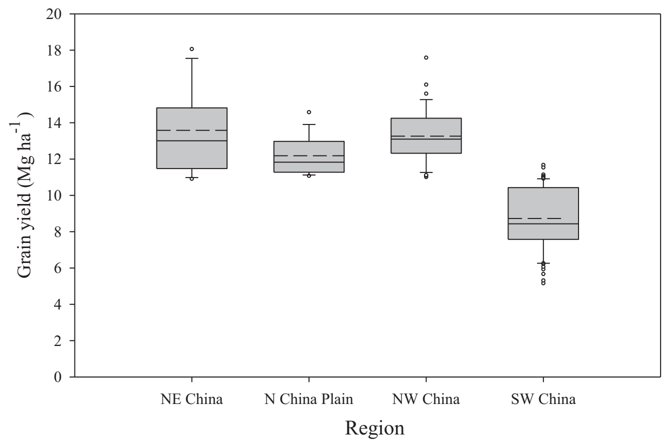

Fig. 3. Experimental yields in Northeast China (NE China, n = 11), North China Plain (N China Plain, n = 18), Northwest China (NW China, n = 37), and Southwest China (SW China, n = 71). Solid and dashed lines indicate medians and means, respectively. Box boundaries indicate upper and lower quartiles, whisker caps indicate 90th and 10th percentiles, and circles indicate outliers.

For rainfed maize, the modeled yield potential averaged 13.9 Mg ha^{-1}, which ranged from 9.2 to 21.0 Mg ha^{-1}, with 25% variation for China as a whole (Table 1). Among the four regions, the highest average yield potential (15.4 Mg ha^{-1}) was in NE China, followed by NW China (14.9 Mg ha^{-1}), N China Plain (13.4 Mg ha^{-1}), and SW China (10.3 Mg ha^{-1}).

3.2. Experimental yields and average farmers' yields

In China, the attainable yield, which was the weighted average of experimental yields, was 12.3 Mg ha^{-1}, ranging from 5.2 Mg ha^{-1} in SW China to 18.1 Mg ha^{-1} in NE China (Fig. 3). NE China had the highest average experimental yield at 13.6 Mg ha^{-1}, and the experimental yields in NW averaged 13.3 Mg ha^{-1}. In the N China Plain, the experimental yield averaged 12.2 Mg ha^{-1}, and SW China had the lowest average experimental yield at 8.7 Mg ha^{-1}. Overall for China, the experimental yield achieved 75% of the yield potential of irrigated maize (ranging from 68% in NW and SW China to 85% in NE China), and 80% of the highest recorded yield (ranging from 75% in the N China Plain to 86% in NE China).

The mean yield from a survey of 5584 farms was 7.4 Mg ha^{-1} and ranged from 1.1 to 16.5 Mg ha^{-1} (Table 2). The average farmers' yield, weighted by maize area in each region, was 7.9 Mg ha^{-1} for all of China. Farmers' yield in NE China averaged 9.3 Mg ha^{-1}, ranging from 2.3 to 16.5 Mg ha^{-1}, which was the highest of the four maize regions. Average farmers' yield was 7.3 Mg ha^{-1} in both N China Plain (2.0–15.0 Mg ha^{-1}) and NW China (2.3–14.3 Mg ha^{-1}). Similarly with yield potential and highest recorded yield, the lowest farmers' yield was in SW China, averaging 5.7 Mg ha^{-1} (1.1–15.0 Mg ha^{-1}).

3.3. Yield gaps

Table 3 shows the calculated modeled, highest recorded and experimental yield gaps (YG_M, YG_R, and YG_E) based on the above yields. For all of China, YG_M of irrigated maize and YG_R averaged 8.6 and 7.6 Mg ha^{-1}, respectively; farmers' fields achieved roughly half of associated yield potential and highest recorded yields. YG_E

Table 2
Descriptive statistics of surveyed farm yields from 2007 to 2008 in China and in the four maize agro-ecological regions: Northeast China (NE China), North China Plain (N China Plain), Northwest China (NW China), and Southwest China (SW China).

	n[a]	Mean	SD[b]	Minimum	25% *Q*[c]	Median	75% *Q*	Maximum
		Mg ha^{-1}						
Total	5584	7.4	2.4	1.1	6.0	7.5	9.0	16.5
Region								
NE China	1248	9.3	2.6	2.3	7.5	9.0	10.7	16.5
N China Plain	2623	7.3	1.7	2.0	6.0	7.5	8.3	15.0
NW China	520	7.3	3.0	2.3	5.3	6.4	9.8	14.3
SW China	1193	5.7	2.1	1.1	4.5	5.3	5.3	15.0

[a] *n*: number of observations.
[b] SD: standard deviation.
[c] *Q*: quartile.

totalled 4.5 Mg ha^{-1}, with farmers achieving 64% of experimental yield.

In the four maize regions, NW China showed both the highest YG_M (12.2 Mg ha^{-1}) and YG_R (10.0 Mg ha^{-1}) for irrigated maize, with farmers' yield achieving 37% and 42% of the yield potential, respectively. The second-largest YG_M and YG_R yield gaps of irrigated maize were 10.3 and 9.0 Mg ha^{-1}, respectively, in the N China Plain, with farmers achieving 41% and 45% of the yield potential of irrigated maize, respectively. In NE China, both YG_M and YG_R of irrigated maize were about 6.5 Mg ha^{-1}, where farmers attained nearly 60% of the yield potential. YG_M and YG_R of irrigated maize averaged 7.1 and 5.3 Mg ha^{-1}, respectively, in SW China, or 44% and 52% of the yield potential was achieved in farmers' fields, respectively.

For rainfed maize, YG_M averaged 6.0 Mg ha^{-1} and farmers achieved 56% of the yield potential for whole of China. Similarly with irrigated maize, NW China showed the highest YG_M (7.6 Mg ha^{-1}) in the four maize regions, with about half of the associated yield potential being attained in farmers' fields. For both NE China and N China Plain, YG_M of rainfed maize averaged 6.1 Mg ha^{-1}, 54–60% of the yield potential was attained by farmers. Among four regions, the lowest YG_M of rainfed maize (4.6 Mg ha^{-1}) was in SW China, 55% of the yield potential was achieved in farmers' fields.

In the N China Plain and NW China, YG_E was 4.9 and 6.0 Mg ha^{-1}, respectively. Thus, the average farmers' yield was 60% of the yield potential in the N China Plain but only 55% in NW China. Nearly 70% of the yield potential was achieved in both NE and SW China, whereas YG_E averaged 4.3 and 3.0 Mg ha^{-1}, respectively.

4. Discussion

For China as a whole, our study showed that YG_M and YG_R ranged from 6.0 to 8.6 Mg ha^{-1}, with about 50% (48–56%) of yield potential being achieved in farmers' fields (Table 3). On average, farmers' yields were only 64% of the experimental yield, with the YG_E being 4.5 Mg ha^{-1}. These gaps are substantially higher than those of other major cereals in China. For instance, the YG_E of rice production is only 1.7 Mg ha^{-1}, and farmers achieve 78% of the experimental yield (Duwayri et al., 2000). These results have various implications for policymakers and researchers concerned with maize production in China. For example, to meet food demand, the total increase in cereals in China over the next several decades could rely on increases in maize productivity, and future maize production could benefit from more attention and investment.

Our finding that farmers achieved about 50% of the yield potential is similar to that of global maize production (Licker et al., 2010), but considerably lower than some specific regions of maize production in other parts of the world. For instance, in the western U.S. corn belt, the average farm yield is more than 80% of the yield potential as simulated by the Hybrid-Maize Model, or 1.3–2.4 Mg ha^{-1} YG_M (Grassini et al., 2011). Nonetheless, the larger maize yield gaps found in the present study indicate the great potential to substantially increase maize yields in China. Among the three yield gaps, attempts to decrease YG_M and YG_R would be most difficult, because they are based on excellent ecological conditions (*e.g.*, better soil) with extensive inputs, regardless of the costs or environmental risks of achieving yield potential and highest recorded yield at the sites (Li and Wang, 2009; Chen et al., 2012b). Considering the similarities between experimental and farmers' field conditions, narrowing YG_E seems to be an efficient tool to increase grain yield over the short term.

Evidence suggests that the large YG_E for maize production in China is mainly related to factors such as inefficient crop management practices (Zhang et al., 2011). Three factors resulted in this large yield gap: (i) low efficiency of light and heat resource use due to low plant density, unsuitable sowing dates, short-duration varieties, and early harvest with incomplete grain filling; (ii) poor water and fertilizer management; and (iii) poor crop management, such as bad sowing quality (non-uniform sowing such as different seed depth and row spacing), large variability in stand uniformity, and improper plant-protection controls. Plant density is one of the most important agronomic attributes that determine grain yield and light and heat resource acquisition. It affects plant architecture, alters growth and developmental patterns, and influences carbohydrate production and partition (Casal et al., 1985). In simulations of yield potential and highest recorded yield, maize density was between 70,000 and 100,000 plants ha^{-1} (Chen et al., 2012b). However, in most farmers' fields in China, maize density is less than 50,000–60,000 plants ha^{-1} (Li and Wang, 2009). In comparison, in the U.S., maize density ranges from 75,000 to 82,500 plants ha^{-1} (Li and Wang, 2010), or 125–165% higher than that in farmers' fields in China. Simulation results from the Hybrid-Maize Model show that maize yields on the N China Plain could be increased 20–40% simply by increasing density from 60,000 to 85,000 plants ha^{-1}. Moreover, most farmers harvest their maize one week before full physiological maturity, resulting in losses of 7–15% of the yield (Wang et al., 2012).

In addition, our investigation of survey data from 5584 farms showed that only 37% of farmers applied a reasonable amount of N fertilizer, whereas 32% applied too much and 31% applied too little. The results from 148 on-farm experiments in seven key summer-maize regions showed that the maize yield could be increased 5% over current farmers' practices through proper N management alone (Cui et al., 2008). For the four maize-producing regions, precipitation was adequate during the maize growing season in NE China, but irrigation was necessary in the other three regions due to seasonal droughts, such as spring and canicular-day droughts in the Sichuan Basin, SW China (Zhang et al., 2010). However, most farmers did not or could not irrigate their maize at the appropriate time due to ignorance and water shortages in NW China and SW China. For example, our investigation showed that less than 30% of farmers irrigated maize at the critical stage of flowering when soil

Table 3
Model-, highest recorded- and experiment-based yield gaps (YG_M, YG_R, and YG_E) and the ratio between the average farmers' yield and the modeled yield potential, highest recorded yield, and experimental yield in China and in the four maize agro-ecological regions: Northeast China (NE China), North China Plain (N China Plain), Northwest China (NW China), and Southwest China (SW China).

		Region				China[a]
		NE China	N China Plain	NW China	SW China	
Yield gaps	YG_M (Mg ha^{-1})	6.6 ± 0.02[b] (6.1 ± 0.02)[c]	10.3 ± 0.01 (6.1 ± 0.02)	12.2 ± 0.04 (7.6 ± 0.06)	7.1 ± 0.03 (4.6 ± 0.04)	8.6 ± 0.02 (6.0 ± 0.03)
	YG_R (Mg ha^{-1})	6.5 ± 0.02	9.0 ± 0.01	10.0 ± 0.04	5.3 ± 0.05	7.6 ± 0.02
	YG_E (Mg ha^{-1})	4.3 ± 0.03	4.9 ± 0.01	6.0 ± 0.02	3.0 ± 0.05	4.5 ± 0.03
The ratio						
Average farmers' yield/yield potential	(%)	58 (60)	41 (54)	37 (49)	44 (55)	48 (56)
Average farmers' yield/highest recorded yield	(%)	59	45	42	52	51
Average farmers' yield/experimental yield	(%)	68	60	55	66	64

[a] Yield gaps and the ratios for China were weighted averages of the maize-growing areas in the four maize regions from 2005 to 2009.
[b] Value of irrigated maize ± standard error.
[c] Value of rainfed maize ± standard error.

water content was low. Yields could be improved 19% if irrigation was applied at this critical stage (Chen et al., 2008).

Nationally, the average topsoil depth for maize production is only 16.5 cm due to the small scale of individual farms in China, where small tractors are widely used to drive rotary cultivators. This is far below the 35.0 cm maize production depth found in the U.S. (Zaidi et al., 2011). As a result, 2- to 5-cm-thick hardpans form quickly in the shallow soil layer after a few trips by tillage machines. Such hardpans inhibit root penetration and cause drainage problems that result in reduced crop yields (Hammond et al., 1981). In addition, most smallholders in China are unable to sow evenly, which results in large variability in plant spacing and stand uniformity when plants emerge. Field studies have shown that about 4–12% of maize yield is sacrificed solely due to uneven seedling emergence (Nafziger et al., 1991; Liu et al., 2004).

The above analysis indicates that one possible way to substantially increase grain yields and close the exploitable yield gap is by improving agronomic management. Thus, the maize cropping system should be redesigned by changing varieties, sowing dates, and planting density to maximize use of solar radiation and favorable temperature periods. Meanwhile, crop and nutrient management and other agronomic strategies should be reformed. Indeed, in a recent study, a Hybrid-Maize Model-driven integrated soil-crop system achieved mean maize yields of 13.0 Mg ha^{-1} in 66 on-farm experimental plots across China, which was 86% of the potential yield simulated by the Hybrid-Maize Model and nearly twice the 6.8 Mg ha^{-1} yield of local farmers' practices (Chen et al., 2011).

However, many steps remain to be taken to substantially narrow the yield gaps between on-farm trials and the hundreds of millions of farm fields in China. A major challenge is developing methods that can be adopted easily by millions of small farmers. Since most farms consisted of several plots of land located in different places, the variation in different regions was one of the most important constraints to recommending novel management for farmers. Thus, analysis in different regions is imperative to find out the best strategies for improving yields and farm recommendations. Simultaneously, improvements need to be made in the dispersion of science based recommendations to agricultural extension workers, perhaps by simplifying recommendations to easily adoptable strategies farmers can follow. A multidisciplinary synthesis of understanding and cooperation among the disciplines of plant science, agronomy, soil science, and agro-ecology and extension, with the aim of developing more ecologically influenced agricultural systems that integrate features of traditional agricultural and ecological knowledge, is essential to increase grain yields (Matson and Vitousek, 2006).

5. Conclusions

Chinese grain production has increased dramatically over the past decades, mainly as a consequence of intensified land management and introduction of new technologies. However, a strong increase in grain demand is expected in the future, which could be fulfilled by further agricultural intensification rather than expansion of cultivated area. Little is known about the potential for yield improvements. Understanding yield potentials and exploitable gaps in current intensive crop production is essential to ensure national food security.

In the present study, we quantified the yield potentials and gaps in China and the major Chinese maize regions. YG_M was 8.6 and 6.0 Mg ha^{-1} for irrigated and rainfed maize, respectively. YG_R and YG_E were 7.6, and 4.5 Mg ha^{-1}, respectively. The average farmers' yield was 48–56% of the yield potential, 51% of the highest recorded yield, and 64% of the experimental yield. The maize yield gap was larger than that of other cereal crops in China and of some maize-producing regions outside of China. Among the three yield gaps,

YG_E appears to have the greatest potential of decreasing in the near future, as improvements in agronomic practices (*e.g.*, integrated soil–crop system management) can help narrow this yield gap. Meanwhile, the cooperation between current research, development and extension systems in maize production should be enhanced to simplify recommendations to easily adoptable strategies farmers can follow. Such improvements, bolstered by more financial support and demonstrations in similar areas around the world, would be valuable steps toward increasing yields to ensure global food security.

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